The Mesoscale Predictability of Terrain Induced Flows

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LONG-TERM GOALS

To develop an understanding of the predictability of small-scale atmospheric circulations appearing in forecasts generated by state-of-the-art high-resolution mesoscale models. Using previously collected observations and archived simulations performed using the Navy's COAMPS model, as well as new simulations, we focus on assessing the predictability of winds, mountain waves and clear air turbulence (CAT) in the lee of the Sierra Nevada.

OBJECTIVES

Specific questions addressed in our research include:

1. How sensitive are downslope winds to atmospheric conditions upstream of the mountain barrier?
2. When such sensitivity is not extreme, can forecast errors in downslope winds and mountain-wave structure be linked to large characteristic errors in the atmospheric conditions forecast to occur on the upstream side of the mountains? Can systematic improvements in COAMPS be identified to remove these errors?
3. What do ensemble forecasts indicate about the sensitivity of downslope winds and mountain waves to the upstream conditions, and how can such forecasts be best used to predict these events?

The answers to these questions are of direct benefit to operational forecasters using COAMPS to produce aviation and other forecasts over complex terrain. Although our focus is on the forecasting of terrain-induced mesoscale disturbances, our findings are likely to be relevant to the predictability of other mesoscale phenomena.

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APPROACH

The P.I., together with Dr. James Doyle of NRL, Monterey and graduate student P. Alex Reinecke, used the COAMPS model to conduct a series of 70-member ensemble simulations of high-wind events observed during the Terrain-Induced Rotors Experiment (T-REX). By examining the ensemble spread, we obtained an unprecedentedly complete description of the sensitivity of mountain waves, CAT and downslope to small variations in the initial conditions.

WORK COMPLETED

We completed the analysis of the sensitivity of mountain waves, CAT and downslope winds to small perturbations in the upstream conditions. We also demonstrated a surprising sensitivity of the simulated mountain waves to numerical resolution. The results from these efforts are detailed below.

RESULTS

This study represents one of the first attempts to systematically document the sensitivity of downslope-wind forecasts to initial conditions in a fully non-linear, three-dimensional NWP mesoscale model. An ensemble of 70 different initial conditions is generated for each of two prototypical downslope-wind events from the T-REX special observing period: IOP 6 (25-26 March, 2006) and IOP 13 (16-17 April, 2006). Consistent with the available data, most of the simulations of IOP-6 show a large-amplitude mountain wave with upper-level tropospheric wave breaking and severe downslope winds. In contrast, wave breaking was not present for the most of the IOP-13 simulations, and consistent with the observations, the downslope winds while still significant, were weaker than in IOP-6. The strong winds in IOP-13 were generated by a layer of high static stability flowing beneath a mid- and upper-tropospheric layer of low stability.

In both cases, the individual ensemble members were ranked according to the forecast intensity of the near surface winds in a region along the lee slope of the Sierras (the “wind speed metric”), and the 10 strongest and 10 weakest ensemble members were grouped into two subsets.

For the wave-breaking simulations (IOP-6), initial-condition errors grow rapidly leading to large variability of the downslope-wind forecast. Fig. 1a, shows the forecast wind speed metric for the members of the strong subset, which can be compared with the same data for the members of the weak subset in Fig. 1b. The wind speeds in the strong and weak subsets diverge rapidly between forecast hours 3 and 6. The difference in the subset means of the wind speed metric at hour six represent the difference between a very severe 41 m s^{-1} downslope winds and a mild 13 m s^{-1} wind event.

The same information is provided for the event with layered static stability, but no wave-breaking (IOP 13) in Fig. 2. In this case the subsets diverge over a period of roughly eight hours. The 26 m s^{-1} winds in the strong subset represent a moderate downslope while the 4 m s^{-1} winds in the weak subset are a non-event.

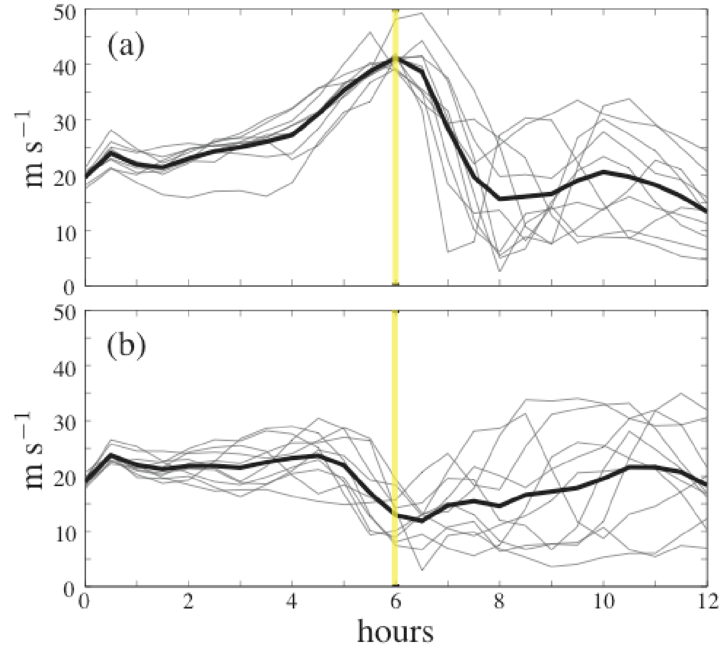

Figure 1: Wind speed metric as a function of forecast hour for each of the members of the (a) strong subset and (b) weak subset. The subset mean is given by the heavy curve. The subset mean forecast winds at hour 6 differ by 28 m s^{-1}.

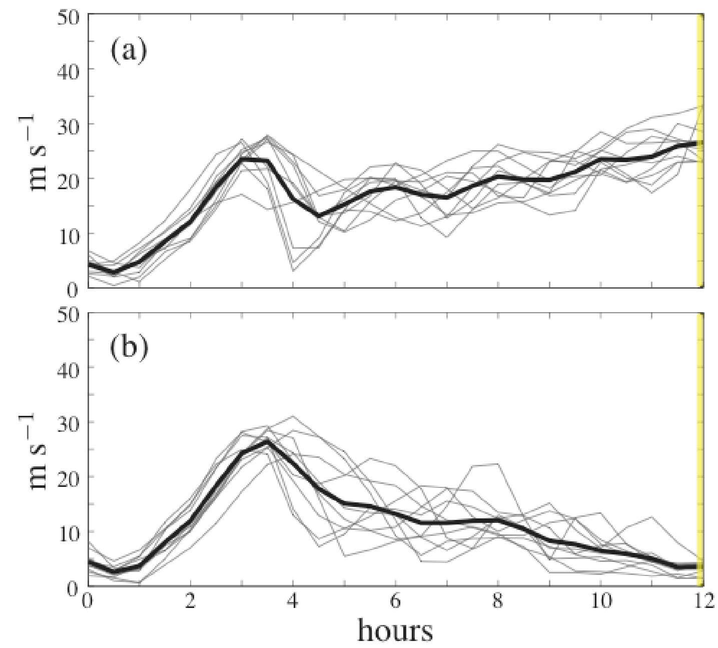

Fig. 2: As in Fig. 1, except for the ten members of the weak subset. The subset mean forecast winds at hour 12 differ by 26 m s^{-1}.

The difference between the means of the strong and weak subsets for these two events is further illustrated in Fig. 3. A very large amplitude mountain wave is present in the strong-subset simulations for the wave-breaking case (IOP 6), with vertical velocities exceeding 14 m s^{-1}. The wave is much weaker in the weak-member subset, with vertical velocities just reaching 8 m s^{-1}. As suggested by the surface wind speeds plotted in Fig. 2, the difference between the response of the strong- and weak-member subsets in IOP 13 is the difference between a moderate and a very weak mountain wave.

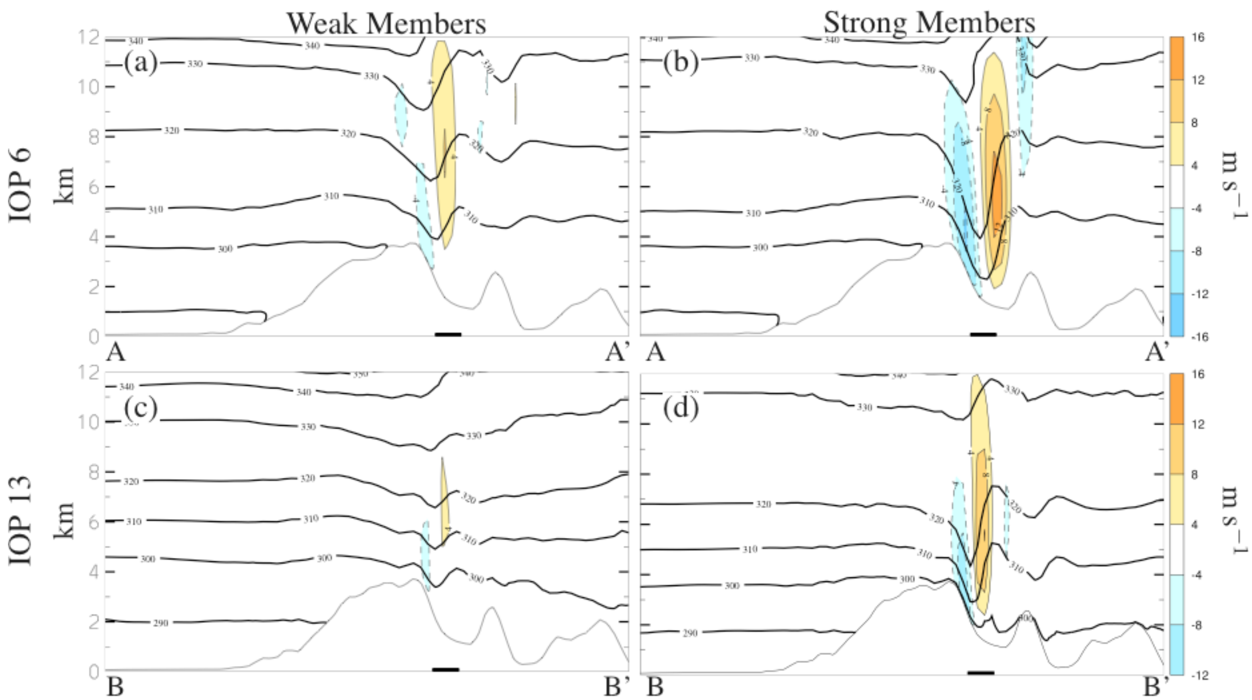

Fig. 3: Isentropes of potential temperature (black curves) and vertical velocity (contoured at 4 m s^{-1} intervals, with the zero contour omitted. The IOP 6 cases are in the top row, those for IOP 13 are on the bottom. The weak subset means are in the left column, the strong subset means are on the right.

Upstream soundings from the mean of the strong- and weak-member simulations were examined for both cases just one hour before the time of the maximum winds in the strong subset. In IOP 6, the wave-breaking case, the differences in the cross-barrier wind speed, potential temperature, and Brunt-Vaisala frequency for the two subsets was generally less than radiosonde observational errors. Such very small differences in the upstream conditions suggest that deterministic operational forecasts may have difficulty accurately predicting the strength of downslope winds and CAT associated with mountain-wave breaking.

For cases with strong low-level static stability, like IOP 13, in which wave breaking did not play a major role, the predictability time-scale appears to be somewhat longer. Upstream soundings from one-hour prior to the time of maximum wind show clear differences between the mean profiles for the strong- and weak-member subsets. For example, a 2-km deep layer of strong static-stability is present directly above crest level for the strong members, whereas, the crest-level static-stability is

considerably weaker for the weak members. Downslope winds that develop in cases like IOP 13 appear to have some degree of predictability at 6-hour lead times, but not at lead times of 12 hours.

Regardless of the mechanism responsible for strong downslope winds, the rapid growth of forecast uncertainty for the IOP-6 and IOP-13 events are considerably shorter than the optimistic view of mountain-wave predictability presented in Klemp and Lilly (1975). Although the predictability results for these two events may not generalize to all mountain-wave and downslope-wind events, they call in question the idea presented in Anthes et al. (1985) that the predictability time scales originally suggested for mesoscale motions by Lorenz (1969) are too pessimistic for terrain induced flows. The difficulties encountered by Nance and Colman (2000) trying to forecast downslope winds with a mesoscale model may also be due, at least in part, to the large initial-condition sensitivities we have documented.

IMPACT/APPLICATIONS

Future operational forecasts of downslope winds, CAT and other terrain induced mesoscale circulations will need to take into account the demonstrated uncertainty in deterministic forecasts by using ensemble techniques.

TRANSITIONS

Alex Reinecke completed his Ph.D and accepted at postdoc at NRL Monterey. While a postdoc at NRL, he was offered tenure-track positions as an assistant professor at McGill and the North Carolina State University. Alex accepted a third offer of a permanent position at NRL, where he continues to work closely with navy researchers on ensemble forecasting and mesoscale predictability.

RELATED PROJECTS

None

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PUBLICATIONS

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HONORS/AWARDS/PRIZES

2007 Alan Berman Research Publication Award (NRL) with James Doyle for the publication "Rotor and sub-rotor dynamics in the lee of three-dimensional terrain."